

# THE MAGIC TELESCOPE PROJECT FOR GAMMA ASTRONOMY ABOVE 10 GeV<sup>a</sup>

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A project to construct a 17 m diameter imaging air Čerenkov telescope, called the MAGIC Telescope, is described. The aim of the project is to close the observation gap in the  $\gamma$ -ray sky extending from 10 GeV as the *highest* energy measurable by space-borne experiments to 300 GeV, the *lowest* energy measurable by the current generation of ground-based Čerenkov telescopes. The MAGIC Telescope will incorporate several new features in order to reach the very low energy threshold. At the same time the new technology will yield an improvement in sensitivity in the energy region where current Čerenkov telescopes are measuring by about an order of magnitude.

## 1 Introduction

Currently the observations of electromagnetic radiation from astrophysical sources and high energy phenomena in the Universe are restricted to energies outside an observation gap extending from  $\approx 10$  GeV to  $\approx 300$  GeV. From the continuation of current measurements into this energy region we expect to find hints or answers to important physics questions in astrophysics, cosmology, and particle physics.

The reason for the observation gap lies in the flux limitation of space-borne instruments for  $\gamma$ -astronomy due to very small collection areas ( $\mathcal{O}(0.1)$  m<sup>2</sup>) which limits the measurements to energies *below* 10 GeV. At the same time the not yet optimized technology of ground-based instruments for  $\gamma$ -astronomy, i.e., the existing Imaging Air Čerenkov Telescopes (IACTs), limits the detection threshold of  $\gamma$ -showers to energies *above* 300 GeV.

In order to close this gap by the comparatively cheap ground-based technique, the 17 m  $\varnothing$  MAGIC Telescope has been designed and important components have been developed during the last 2 years<sup>1</sup>.

## 2 Physics Goals

Some of the physics goals of the MAGIC Telescope project can be summarized as follows:

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<sup>a</sup>Invited talk at the 36th INFN ELOISATRON Workshop on NEW DETECTORS, Erice, November 1997.

- Most of the blazar type active galactic nuclei (AGN) that have been detected by the EGRET detector<sup>2</sup> onboard the Compton Gamma Ray Observatory (CGRO) below 10 GeV must exhibit cutoff features below 300 GeV. The reason is that of the more than 60 blazars detected by EGRET below 10 GeV only 2 (+1) have been detected by the ground-based detectors, although the average fluxes of many of them would have been within the sensitivity range of the IACTs for the naive extrapolation of the spectra, i.e. assuming a continuation of the power law spectra as measured by EGRET. Both the coverage of the observation gap as well as an improvement of the sensitivity at current energies is therefore needed.
- The visible universe in high energy photons is limited because of pair production on low energy diffuse background photons. Due to the low energy photon density varying strongly with energy an instrument with a lower threshold compared to current IACTs will have access to a much larger fraction of the Hubble volume. Current IACTs view the universe out to  $z \approx 0.1$  ( $\approx 1.8$  billion light years for  $H_0 = 50 \text{ km sec}^{-1} \text{Mpc}^{-1}$ ). The MAGIC Telescope will be able to observe objects out to very early times, i.e., out to  $z \approx 2.8$ .
- Gamma-Ray Bursts (GRBs) will also be observable out to cosmological distances. Extrapolation of the GRBs detected by EGRET reveal that even medium strength bursts will yield very large  $\gamma$  rates detectable by the MAGIC Telescope, i.e., rates up to the order of kHz.
- Supernova remnants (SNRs) as the sites of cosmic ray acceleration in most models of the cosmic ray origin seem to be more complex than previously believed<sup>3</sup>. Although three SNRs have been observed above 300 GeV (Crab nebula, Vela, and SN1006) the question of the origin of the cosmic rays is far from answered. More sensitive measurements at lower energies will be of great importance.
- Of the more than 800 known radio pulsars EGRET has revealed 7 to emit pulsed  $\gamma$ -rays up to  $\approx 10$  GeV. To clarify the production mechanism measurements in the 10 GeV to 100 GeV energy domain are crucial. In some models no pulsed emission is expected beyond some tens of GeV.
- The Dark Matter in the universe visible most pronounced in the rotation curves of galaxies may exist in form of the lightest supersymmetric particle. In most astrophysical models of the dark halo of our Galaxy these particles would cluster in the centre of the Galaxy opening up the

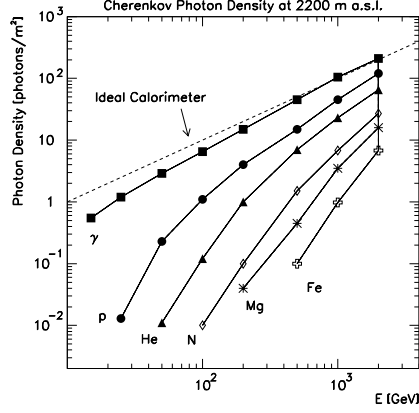


Figure 1: Photon density (300-600 nm) at 2000 m asl as a function of incident energy and particle. The photon density is averaged over an area of 50 000 m<sup>2</sup>. Taken from ref.<sup>5</sup>.

possibility of a  $\gamma$  annihilation line and a  $\gamma$  continuum to be measurable by IACTs with the preferred energy around 100 GeV.

### 3 Basic Considerations

As shown in fig. 1 the Čerenkov light pool at 2200 m above sea level (asl) for  $\gamma$  induced air showers is almost linearly dependent on the incident  $\gamma$  energy. Current IACTs like the 10 m  $\odot$  Whipple telescope in Arizona<sup>4</sup> have a photon sensitivity of about 35 photons/m<sup>2</sup> corresponding to an  $\gamma$  energy threshold of about 300 GeV. As hadron induced air showers produce less Čerenkov light than  $\gamma$  induced ones, a natural  $\gamma$ /hadron separation at the threshold is provided. From fig. 1 one can deduce that this inherent hadron suppression factor rises with falling energy. A telescope that would be sensitive at  $\mathcal{O}(10)$  GeV therefore does not need to have excellent hadron rejection capabilities based on image analyses already at the threshold. Note that in general the different development of  $\gamma$  and hadron induced air showers is exploited for the suppression of the hadronic component by an image analysis of the showers recorded with highly granular cameras.

Table 1 shows a comparison of some existing air Čerenkov detectors in terms of sensitivity and corresponding physics energy thresholds for  $\gamma$ -rays, and the minimum number of photoelectrons (ph.e.s) that have to be recorded

Table 1: Sensitivity of operating, to be upgraded, and planned Čerenkov telescopes in terms of the minimum number of photons/m<sup>2</sup> in the Čerenkov light pool. In addition the required number of photoelectrons for reconstruction of the image parameters is given. Note that physics energy thresholds are given. Trigger thresholds generally are lower by 15 to 30%. The two energy values quoted for VERITAS and HESS correspond to a single telescope or the telescope system, respectively.

Telescope) (-Array)	Mirror size (m <sup>2</sup> )	Sensitivity (Ph./m <sup>2</sup> )	E <sub>thres</sub> after cuts	ph.e./image
Operating Telescopes				
HEGRA CT1	5	220	1.5 TeV	≥ 100
HEGRA CT3-6	8.4	150	700 GeV	≥ 100
CAT	18	35 (?)	300 GeV (?)	≥ 30
WHIPPLE	74	35	300 GeV	≥ 300
Upgraded Telescopes				
WHIPPLE 98	74	16 (?)	100 GeV	≥ 100
Planned Telescopes				
VERITAS	9 x 74	16 (?)	70 - 100 GeV	≥ 100
HESS	16 x 74 (?)	14 (?)	70 - 100 GeV (?)	≥ 100
MAGIC	234	1.1	12 - 14 GeV	≥ 80
MAGIC (APD)	234	0.6	≈ 7 GeV	≥ 120

for a successful image analysis. The trigger threshold energies usually are lower by 15 - 30%. Note, that the minimum number of ph.e.s per image required for a successful image analysis is a function of the pixel size, the noise level, and the speed of the camera which ultimately is limited by the degree of isochronicity of the mirrors. The first and to a certain extend the third influences have e.g. been optimized by the CAT collaboration<sup>6</sup> in order to achieve a low threshold with a comparatively small mirror area. In the case of the MAGIC Telescope, however, the very low photon densities cause the first and second influences to dominate; hence the requirement of at least 80 ph.e.s for successful MAGIC Telescope image analysis. Note also that low noise avalanche photo diodes (APDs) that are required for  $\gamma$ -ray astronomy are not yet available. The development, however, is progressing fast<sup>7,8,9</sup> and APDs, once they are available, will allow for a further lowering of the energy threshold as indicated in table 1.

## 4 The Technical Realization

Compared to the currently largest operating Whipple telescope with a mirror dish diameter of 10 m, the MAGIC Telescope will need a sensitivity that is better by a factor of  $\approx 15$  (see table 1) in order to reach the  $\mathcal{O}(10)$  GeV threshold. In addition the sensitivity to the night sky background (NSB) has to be reduced. These goals will be met by the MAGIC Telescope technology items that have either been developed or which is existing technology that will be adapted to  $\gamma$ -ray astronomy. The steps and the gain in ph.e.s connected with the steps are summarized in table 2.

Table 2: Steps to lower the energy threshold by raising the gain in ph.e.s for image analysis. The gain in sensitivity for strong signals will be linear, for weak signals it will go like the square root of the quoted numbers.

Technology step	Gain in ph.e.s
Enlarging the mirror area (10 m $\varnothing \rightarrow$ 17 m $\varnothing$ )	$\approx 3$
$\approx 100\%$ light collection efficiency in camera (Winston cones)	1 - 1.5
Application of <b>red sensitive</b> light sensors	$\approx 3$
Reduction of excessive noise factor (not multiplicative)	(1.3 - 2)
Improved ph.e. collection efficiency	$\approx 1.3$
Other small improvements	1.1 - 1.3

Note, that the gain in sensitivity is linear as long as the signal is large compared to the NSB noise. If the signal and noise are of comparable strength, the gain will only be proportional to the square root of the gain factor.

The reduction of the NSB influence will be facilitated by reducing the time spread of the photons arriving at the camera from different parts of the mirror dish with the help of an isochronous mirror dish, i.e., of paraboloid shape. In addition we will reduce the readout time to the intrinsic signal width by the use of a 300 MHz Flash-ADC readout, we shall minimize the read out image area by using small pixels, and we shall minimize background light incident under large angles by using optimized light guides.

### 4.1 The MAGIC Telescope

The steps necessary to raise the sensitivity as summarized in table 2 are realized by the new technology or the adaption of technology items to  $\gamma$  astronomy for the MAGIC Telescope (see fig. 2). These items are:

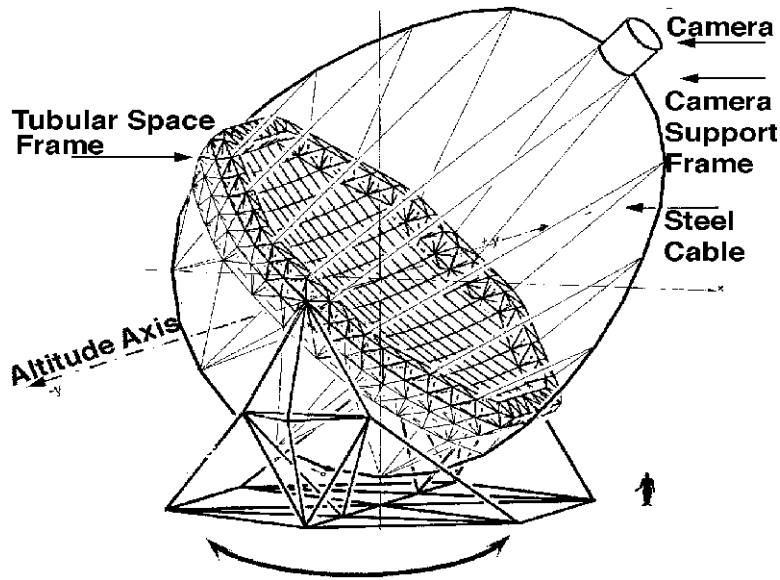


Figure 2: Sketch of the 17 m MAGIC Telescope.

- A light weight carbon-fibre space frame which will enable us to increase the mirror dish diameter to 17 m. At the same time the inertia will be kept low for rapid turning capability for GRB searches.
- Newly developed light weight all-Aluminium mirrors with internal heating.
- An active mirror control for reducing the remaining deformations in the mirror frame during telescope turning.
- For the camera we are considering three variants:
  - a camera equipped with classical photo multiplier tubes (PMTs), i.e., a copy of the now operational 271 pixel camera of the HEGRA telescopes;
  - a camera equipped with hybrid PMTs with high quantum efficiency (QE) also in the red part of the spectrum ( $QE \approx 45\%$ );
  - as a future option we anticipate the use of silicon avalanche photo diodes (APDs) with about 80% QE. Here still further major developments are needed, however.

- The analog signals from the camera PMTs (APDs) will be transported from the camera to the electronics container at ground level by optical fibres. This will result in a small camera weight and allows constant access to the electronics on the ground.
- The signals will be digitized by 8-bit Flash-ADCs with a sampling rate  $\geq 300$  MHz. Besides minimizing the noise this will give the precise shape of the signals which then can be exploited for hadron background suppression. It will also provide buffering for higher level trigger decisions and will allow to add more telescopes in the future in order to build the first large  $\gamma$ -ray observatory<sup>11</sup>.

#### 4.2 Some MAGIC Telescope technology elements in detail

The three-layer space frame will be made from carbon-fibre epoxy tubes which are both lightweight and rigid. A finite element analysis has shown that the residual deformations can be kept below 3.5 mm with respect to the nominal curvature at any position for a total weight of the frame and mirror elements of less than 9 tons. Fig. 3 shows a computer generated view of the space frame with the three layers of 1m,  $\approx 1.14 \cdot \sqrt{2}$  m, and  $\approx 2$  m grid spacing. A circumpherical ring of 1m height is added to further stiffen the frame.

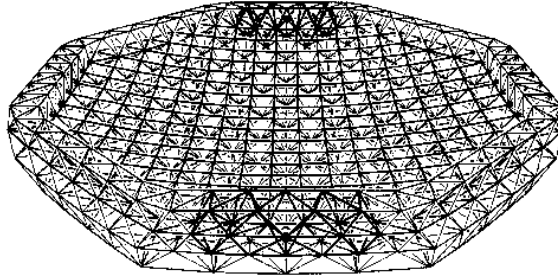


Figure 3: Computer generated view of the space frame consisting out of a 3 layer structure stiffened at the circumference by an additional 1 m high structure. The thicker lines correspond to the inset welded steel frame construction in the area of the axis of the dish.

The mirror will be tessellated with a basic element size of  $50 \times 50$  cm<sup>2</sup>. These new lightweight elements are sandwich aluminium panels, equipped with internal heating to prevent dew and ice deposits. By diamond turning a high quality surface with a residual roughness below 10 nm is achieved yielding a typical focal spot size of 6 mm at a focal length of 34 m. The preproduction

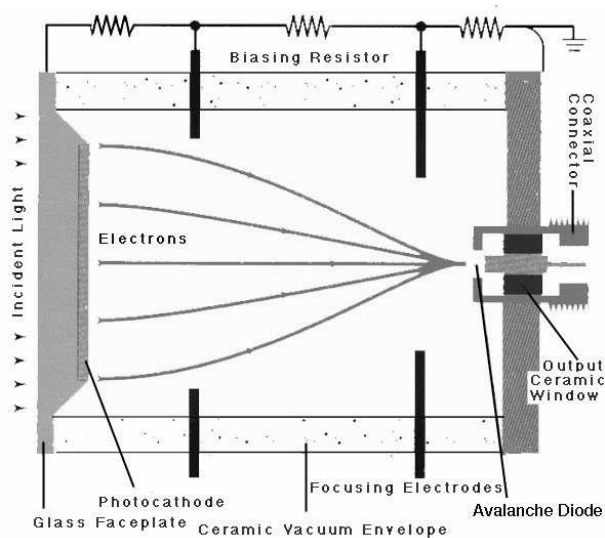


Figure 4: Cross section of a hybrid photomultiplier with avalanche diode readout.

series of these mirrors that have been installed on the HEGRA CT1 prototype telescope have already shown the soundness of this design.

The active mirror control has been newly developed and successfully tested in the laboratory. It works on panels of 4 preadjusted mirror elements which can be tilted by two stepping motors. A videocamera will record the position of a laser pointer on the casing of the camera and from the comparison of the actual spot position with the nominal one the steering commands will be derived.

The camera will have a field-of view with a diameter of  $3.6^\circ$  with a pixel size of  $0.1^\circ$  in the central region of  $2.5^\circ$  and a coarser pixelisation ( $0.2^\circ$ ) in the outer part.

The photon sensor we intend to use is of the hybrid PMT type (hybrid photon detector, HPD) with a GaAsP photocathode as e.g. produced by INTEVAC (see fig. 4)<sup>10</sup>.

These type of HPDs are characterized by a considerably higher QE of  $\approx 45\%$  that extends into the red part of the spectrum. The QE in the blue will be enhanced to the same level by the application of a wavelength shifter dye. The second main element of these detectors, the readout diode, which in the original INTEVAC design was a GaAs Pin diode, for the MAGIC Telescope



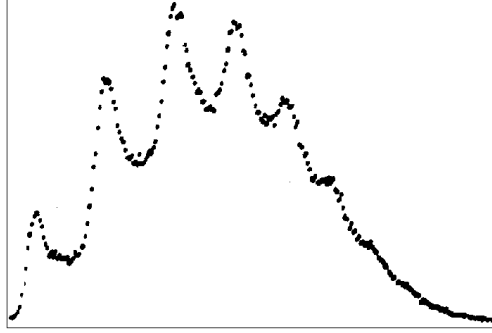


Figure 5: Pulse height spectrum of a modified Intevac IPC when illuminated by a fast blue LED pulser. Settings:  $U_{c-a} = 10$  kV;  $U_{AP} = 30.0$  V,  $\tau = 50$  ns.

application will have to be exchanged by a Si avalanche diode (AD) in order to achieve a gain of 30,000 - 50,000 already with an  $U_{cathode-anode}(U_{c-a})$  of the order of 5 kV. Note that the connected loss in speed will not be crucial for our application but the low operation voltage will considerably ease the operation under harsh environmental conditions and will allow the use of cheaper and less complex transimpedance amplifiers compared to charge sensitive ones. The pulse height spectrum recorded with a prototype HPD using a blue LED pulser of 5 ns FWHM and  $\langle n_{photon} \rangle \approx 6-8$  is shown in fig. 5. The complete electronics setup for a single channel is shown in fig. 6.

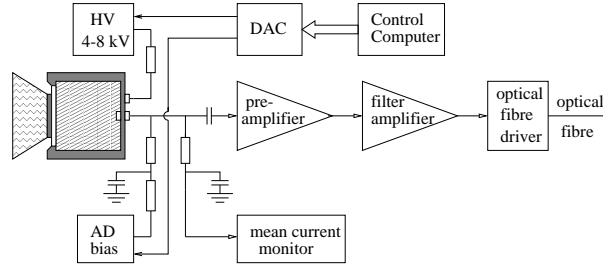


Figure 6: Basic block diagram of a single camera pixel readout chain.

The transport of analog PMT pulses with optical fibres has been developed for the AMANDA collaboration<sup>12</sup>. For the MAGIC Telescope we are currently performing measurements aimed at optimizing the transmitter and receiver ends for our needs.

## 5 Performance

We have performed extensive Monte Carlo simulations of the MAGIC Telescope in order to optimize the design and to get performance estimates. The trigger threshold (defined as the maximum differential counting rate) is slightly below 10 GeV. The effective collection area will reach  $\approx 10^5 \text{ m}^2$  at about 100 GeV (for observations near the zenith) and will be as large as  $6 \cdot 10^6 \text{ m}^2$  at very large zenith angles. The corresponding sensitivity is shown in fig.7 together with the numbers for some current IACTs and for the EGRET detector. Also shown is the sensitivity as quoted for the planned 9-telescope array VERITAS and the planned satellite detector GLAST.

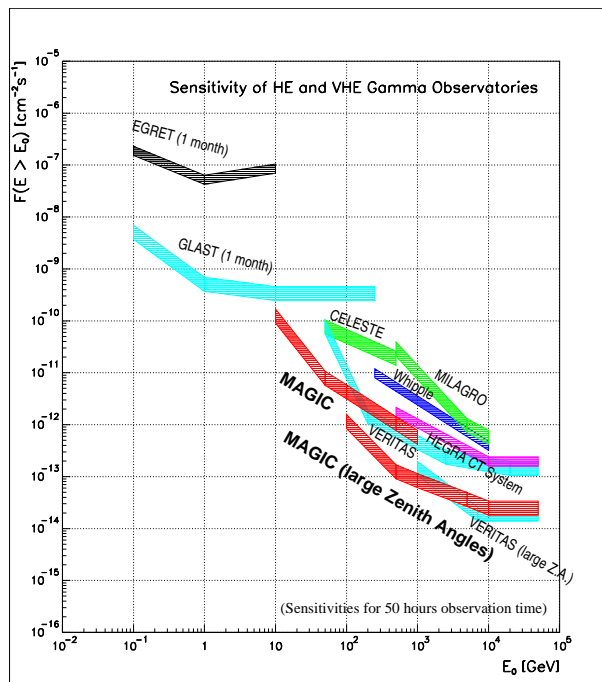


Figure 7: Comparison of the point-source sensitivity of the MAGIC Telescope at  $0^\circ$  zenith angle and at zenith angles of about  $75^\circ$  (denoted MAGIC (large Zenith Angles)) to the point-source sensitivity of existing (CELESTE, HEGRA CT system, MILAGRO, Whipple) or planned ground-based installations (VERITAS) and to the sensitivity within 1 month of observations for the existing (EGRET) and planned (GLAST) space-borne high energy  $\gamma$ -ray experiments.

## 6 Conclusions

The 17 m diameter MAGIC Telescope has been designed to measure  $\gamma$ -rays with energies above 10 GeV. Most of the new technology for this telescope has been developed during the last 2 years<sup>1</sup>. Using innovative elements it will be possible to close the existing observation gap in the electromagnetic spectrum for about 1% (!) of the cost of a satellite experiment, which until now was believed to be necessary in order to do measurements in this energy domain. At the same time the sensitivity in the energy region of current Čerenkov telescopes will be improved by up to an order of magnitude. The innovative elements of the MAGIC Telescope technology will very likely be the basis for all IACTs of the next generation. We estimate the hardware-price of the telescope to be around 3.5 M\$. The construction time will be 2.5 - 3.5 years.

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